

Tension structures for solar electricity generation

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Abstract

Large scale solar thermal electricity generation is technically feasible and could soon become economically competitive, if more efforts for its introduction are made. In the two technologies developed by the author and his team, stretched metal membrane solar concentrators for heliostats and Dish/Stirling systems and the solar chimneys tension structures play a decisive role. Thus solar electricity generation has become a new and promising field of activity for structural engineers. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Solar electricity generation; Tension structures; Solar chimney; Direct electricity generation; Metal membrane solar concentrator

1. Motivation

This earth's and mankind's future is mainly determined by whether or not we will succeed in humanely reducing the population increase in the so-called Third World. The key for this is raising the standard of living and overcoming the tremendous poverty and suffering there.

Today, traditional means will no longer suffice. Countries owing more than 20% of their Gross National Product to agriculture have their people starving.

Progress needs energy. Energy consumption increases in proportion to the prosperity, and with it the population decreases exponentially. (Fig. 1)

The poor developing countries have hardly any energy and double their population every 15 to 30 years. The consequences are obvious: Civil wars and fundamentalism. Supplying them with only a decent and viable minimum of energy — by no means as much as ours — world energy consumption rapidly multiplies and increases exponentially.

Which source could supply this energy without an environmental break-down, (because these countries have no funds for environmental protection) without safety hazards (because these countries have no safety history for nuclear power plants) and without rapidly

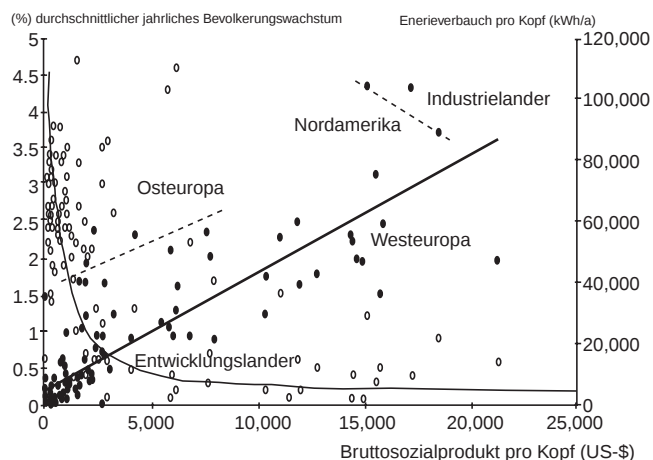


Fig. 1. Energy consumption (Energieverbrauch) and population increase (Bevölkerungszuwachs) as a function of GNP (Bruttonsozialprodukt) or standard of living.

exhausting their natural resources at the expense of future generations? The source is the sun. The poor countries are the ones with high solar irradiation and vast deserts.

All this is widely known, as stated in the Agenda 21 of the Rio-UN-Conference, everybody is talking about it, but much more should really be done — a new field for structural engineers.

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2. Technologies for direct solar electricity generation

When addressing solar electricity generation, it is common to distinguish between small decentralised and large centralised power generation. In the first case a unit has, say, an output of some 100 kW maximum and is therefore likely to be installed in remote areas away from the grid. Centralised generation means large-scale solar power plants feeding the grid with 10 to 500 MW per unit and capable of someday, partially replacing present large-scale fossil or nuclear electricity generation. However, bearing in mind the successful operation of hydro-electric power plants, this is nothing less than a utopian goal.

According to the present state of the art, the following technologies for *direct*, active solar electricity generation are widely known and generally have been found to be feasible:

2.1. Centralised large-scale electricity generation

- Distributed collector systems (DCS) with parabolic trough collectors
- Central receiver systems (CRS) with heliostats
- Solar chimneys with flat glass collectors

2.2. Decentralised small-scale electricity generation

- Dish/Stirling systems (D/S)
- Photovoltaics (PV)

With the exception of PV, all these systems are solar *thermal* power plants. Both solar chimneys and photovoltaics are also able to utilise *diffuse* solar radiation, which suggests that the solar chimney provides the only technology for large-scale utilisation in the regions with substantial diffuse global radiation, i.e. major parts of Asia, South of Africa and South America.

This paper will concentrate on D/S, CRS and Solar Chimneys, because their efficiency heavily depends on tension structures — as introduced by the author and his team.

Since PV and DCS do not utilise tension structures, they will not be discussed here, rightly so for PV, because, in spite of all financial support and advertisements they are still too far away from economy, not so for DCS which have through large-scale prototypes in California demonstrated, that they are feasible. However, recently the manufacturer ran into financial difficulties due to the withdrawal of subsidies and unfortunately the future of this system is uncertain [1–3].

However, to acknowledge the possible future role of DCS in places with ample direct (as against diffuse) solar radiation, their basic features are given.

Line-focusing parabolic trough collectors, each 100 m long and 6 m wide, are made from hundreds of curved

mirror segments. These troughs are suspended in such a way that they track the sun around one axis only. The structures supporting the curved mirror segments should be light, stiff and easy to manufacture. Future aperture widths of 9 m represent challenging structural design problems. The solar radiation bundles on glass/metal tubes which are placed along the focal lines of the troughs. These tubes transport a heat transfer medium, at present a synthetic oil but in future possibly just water-steam. This medium is collected and transferred to a conventional steam power plant consisting of heat exchangers, turbines, generators, and a cooling tower, consuming sweet water, which may not be readily available in sunny countries.

In case of prolonged lack of solar radiation, a gas-burning capability may be added. This back-up avoids the need for costly thermal storage and guarantees continuous electricity supply, a requirement utilities certainly appreciate and pay for correspondingly, though they disrespectfully therefore call DCS just fuel-savers.

3. Dish/Stirling systems with tensioned metal membrane solar dish concentrators

Tension structures, especially if double curved, stand for an ideal load bearing behaviour. They may be pre-stressed mechanically from their edges, resulting in negative curvature or saddle shapes or pneumatically resulting in positive curvature or spherical shapes. If, for better durability, they are to be manufactured from thin metal membranes (say 0.2–0.5 mm thick) instead of textile material, the common approach of shop fabrication by use of a predetermined cutting pattern fails, since double curved metal sheets would crackle and spoil if folded for transport from the shop to the site. On the other side, especially stainless steel sheet is extremely ductile and therefore the fabrication of double curved surfaces from plane sheet through plastic deformation appears to be the right approach in this case. So, for example a dodecahedron becomes a sphere through inflation (Fig. 2) or two plane sheets, welded from strips and clamped between two compression rings, become a cushion (Fig. 3). The latter could serve as a light weight roof for a circular silo or an arena if a small permanent internal pressure is maintained. Whilst during such tests with this purpose in mind several years ago, we observed with increasing internal pressure respectively strain of the sheet, all welding wrinkles disappearing and a perfectly smooth spherical shape evolving — a surface with optical quality (Fig. 4). This led to the idea of reversing the process, i.e. to evacuate a short cylindrical drum thus producing a concave surface respectively two on either side one of which should be fabricated with special care and could be used as a solar concentrator (Fig. 5). In fact for heliostats (for CRS-systems, see chapter 4 of this

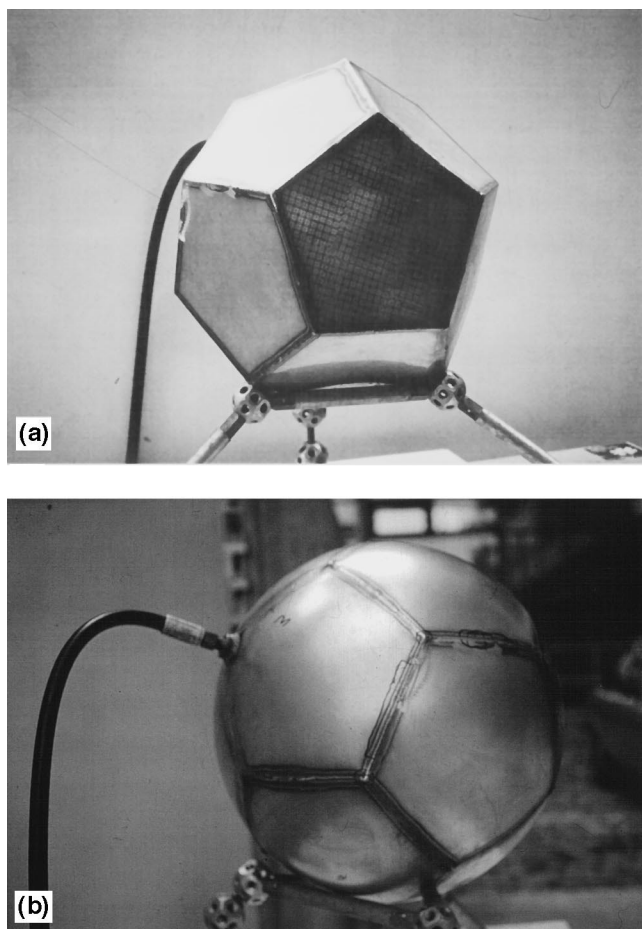


Fig. 2. A dodecahedron welded from 12 equal plane stainless steel sheet pentagons. a) before and b) after inflation.

paper) with a long focal length the membrane remains in its elastic range. For D/S-systems, however, the membrane is plastically deformed to the desired shape by air pressure and hydraulic load (Fig. 6). Mirror glass is bonded to the reflecting surface. When the concentrator is in operation, the shape of the membrane is kept constant by a partial vacuum in the interior of the concentrator.

In the D/S-system, a concave concentrator several meters in diameter is suspended in such a way that it can track the sun. At the focal point of the concentrator, an energy converter is suspended which converts the concentrated solar heat into electricity.

There are two different tracking modes - azimuthal and polar (Fig. 7). The distinctive feature of the polar tracking mode is that the two rotational axes are separated into diurnal (earth rotation) and seasonal tracking (orbit of the earth around the sun) (Fig. 8). The concentrator has to be rotated around the diurnal or polar axis at a constant speed of 15° per hour, corresponding to the rotation of the earth. The seasonal axis has to be adjusted only once a day. For azimuthal tracking the concentrator follows the sun by rotating around two axes perpendicu-

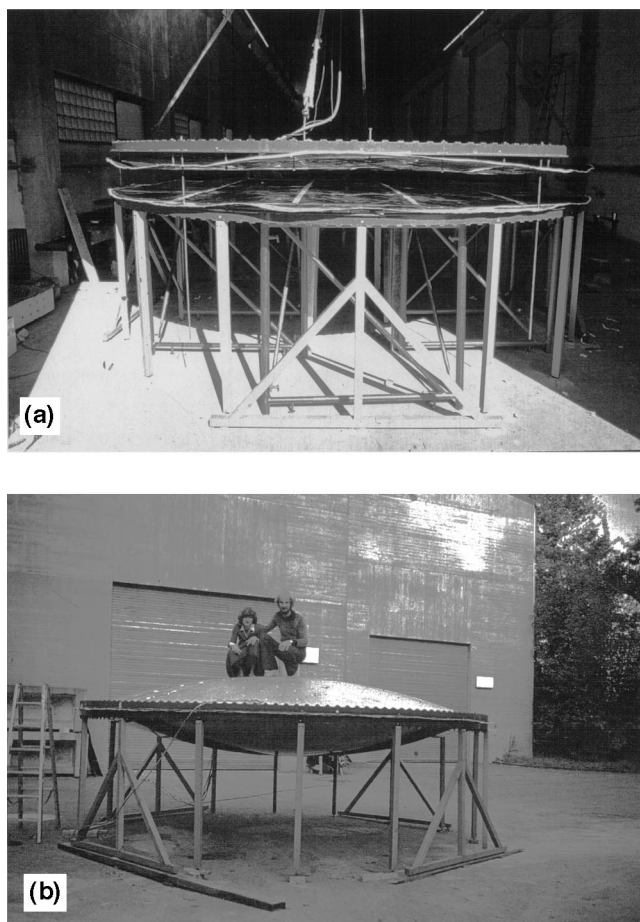


Fig. 3. Metal membrane cushion formed from plane sheet by inflation. a) two sheets are clamped between two steel rings, b) the interior is inflated and the two sheets deform plastically.

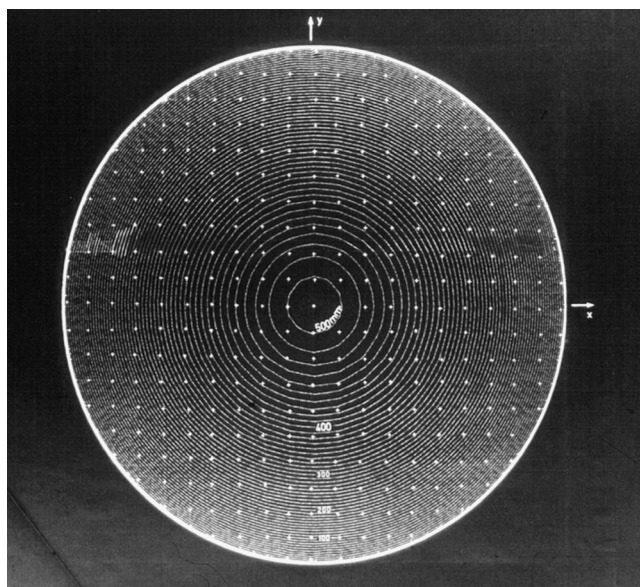


Fig. 4. The contour lines of the cushion (Fig. 3) at 100 mm and at 500 mm rise of the dome.

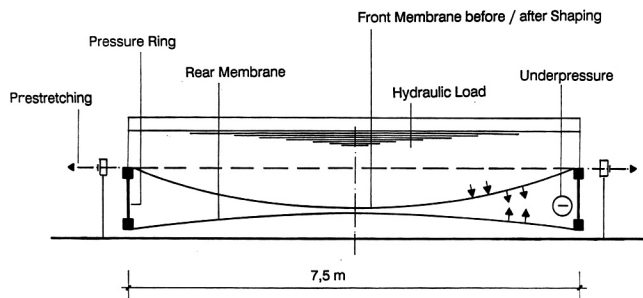


Fig. 5. Forming the membranes of a dish concentrator by deflection and water loading.



Fig. 6. Forming a stretched metal membrane concentrator by underpressure and hydraulic load. a) placing the second membrane, b) water loading.

lar to each other (Fig. 9). In order to follow the sun continuously, both axes have to rotate permanently, with the speeds of both drives changing during the whole day. This requires electronic piloting and sophisticated step-motors. Obviously, polar tracking is superior for decentralised, remote application of dishes, whereas azimuthal tracking suits clusters of heliostats or dishes.

The energy conversion system consists of a Stirling

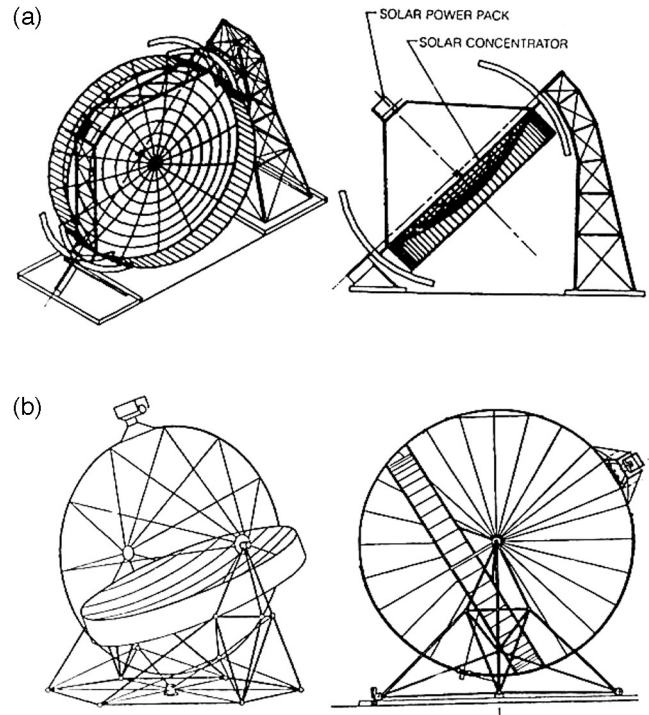


Fig. 7. Tracking of D/S-systems. a) polar, b) azimuthal.

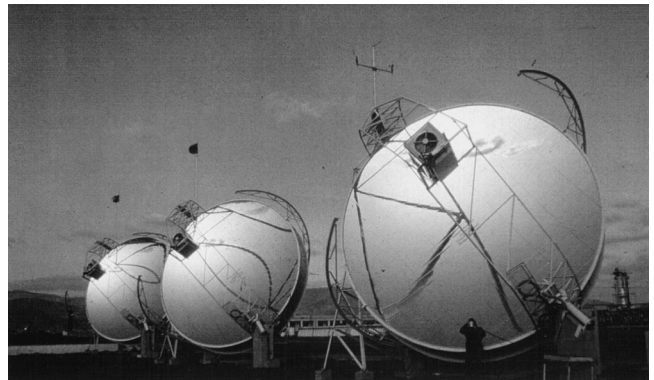


Fig. 8. Polar tracking. Three 7.5 m/9 kW Dish/Stirling systems in Almeria, Spain.

engine with a receiver located at the focal point of the concentrator; the reflected solar rays heat the working gas (hydrogen) of the engine. A generator is coupled directly to the engine to produce electricity.

Since each unit is capable of fully independent operation, as many concentrators as desired can be operated in conjunction, according to requirements. They can be operated both in “grid connection” or “stand-alone” modes. By hybrid operation using fossil or, better still, biogas, storage devices such as batteries can be avoided.

Power plants with concentrators are capable of an overall efficiency (defined as the ratio of the electricity output to the solar irradiance over the concentrator surface) of up to 27%. This has never been achieved with other types of solar plants. As the membrane fabrication

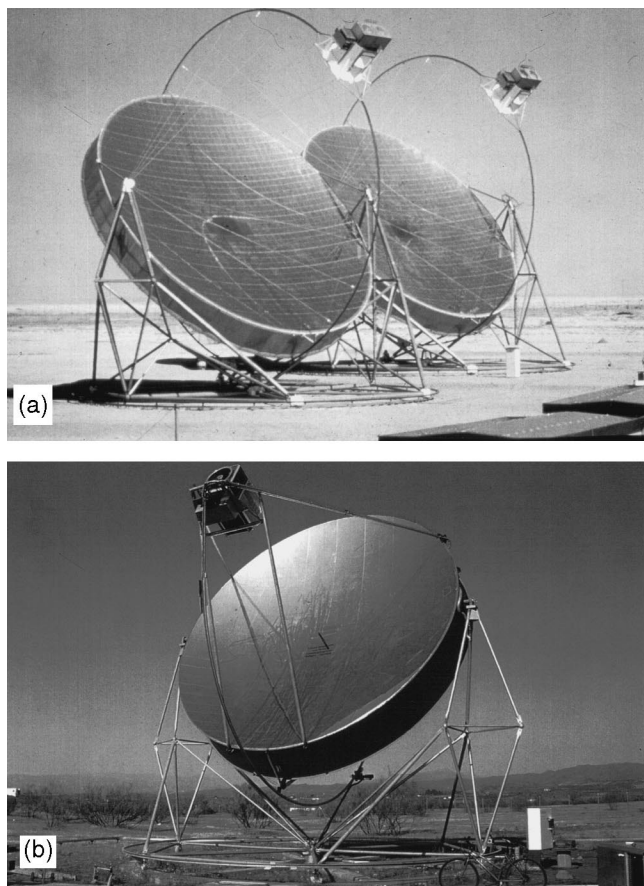


Fig. 9. Azimuthal tracking. a) Two 17 m/50 kW Dish/Stirling systems in Riyadh, Saudi Arabia, b) 8 m/11 kW Dish/Stirling system in Almeria, Spain.

method used for the concentrator is relatively inexpensive, such systems make economical electricity generation a real possibility.

With carefully planned technology transfer, such power plants could readily be fabricated in less developed countries. On the other hand, the design has to consider the effects of extreme thermal expansion and special high-temperature-resistant materials have to be used for the receiver tubes in order to achieve long service life.

In 1985, after constructing a test facility in Germany, two concentrators with 17 m diameters were installed in Saudi Arabia, co-sponsored by German Ministry of Research and Technology and the King Abdul Aziz City for Science and Technology in Riyadh (Fig. 9a). Their power output is 50 kW_e each. After the “usual” initial problems, especially with the Stirling engines, both are operating according to expectations.

With the experience gained from such projects, a further step of development was started in 1987 with the goal of developing a smaller and extremely robust plant using polar tracking for installation in remote regions and capable of operation by unskilled owners/users. With a 7.5 m diameter the power output is 9 kW_e. After

testing a prototype in Stuttgart, three units were installed at the Plataforma Solar test facility at Almeria, Spain (Fig. 8).

Due to the low thermal inertia of the system, power output is almost instantaneous (Fig. 10). Thus, on cloudless days the very first hours of sunshine can be exploited, and daily operation time is almost as long as the daylight hours. Even on days with mixed weather conditions these systems demonstrate good efficiency due to the fast system response and the efficiency of the Stirling engine under partial load.

Since May 1992, all three polar tracking units are operating from sunrise to sunset whenever weather permits. As of October 1997, the three systems will have accumulated approximately 30 000 operating hours — a world record for such systems.

During the summer of this year 1997 three further units with improved Stirling engines and simplified azimuthal tracking have been installed in Almeria and started operation (Fig. 9b).

The expected cost of the 8.5 m/10 kW system, based on a production rate of 10 000 units per year, is given in Fig. 11 and the energy production costs per kWh in Fig. 12, showing that solar electricity produced by D/S-systems is competitive with small diesel generators and by a factor of 5 cheaper than PV [4,5].

4. Central receiver systems (CRS) with stretched membrane heliostats

Forming a huge faceted double-curved concentrator, a large number of heliostats is arranged on the ground around a tower. A central receiver is placed on top of this tower, between 50 and 150 m above ground. Solar radiation is reflected to the receiver, heating a heat transfer medium which may be air, water-steam, liquid sodium or melted salt and, correspondingly, the process temperatures vary from 550 to 1000°C. Beyond that, as

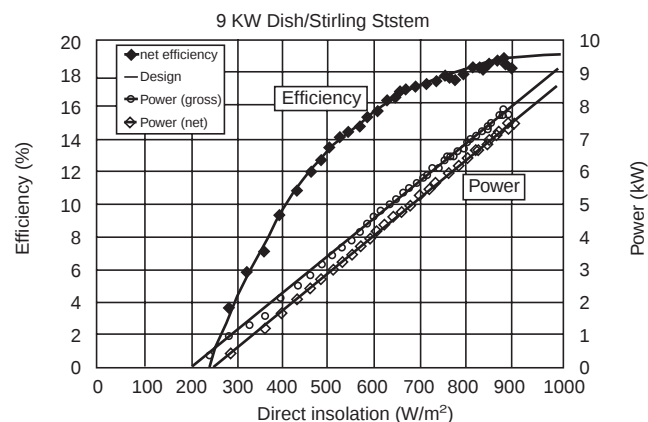


Fig. 10. Input/output characteristics and net efficiency of 7.5 m/9 kW Dish/Stirling system in Almeria, Spain.

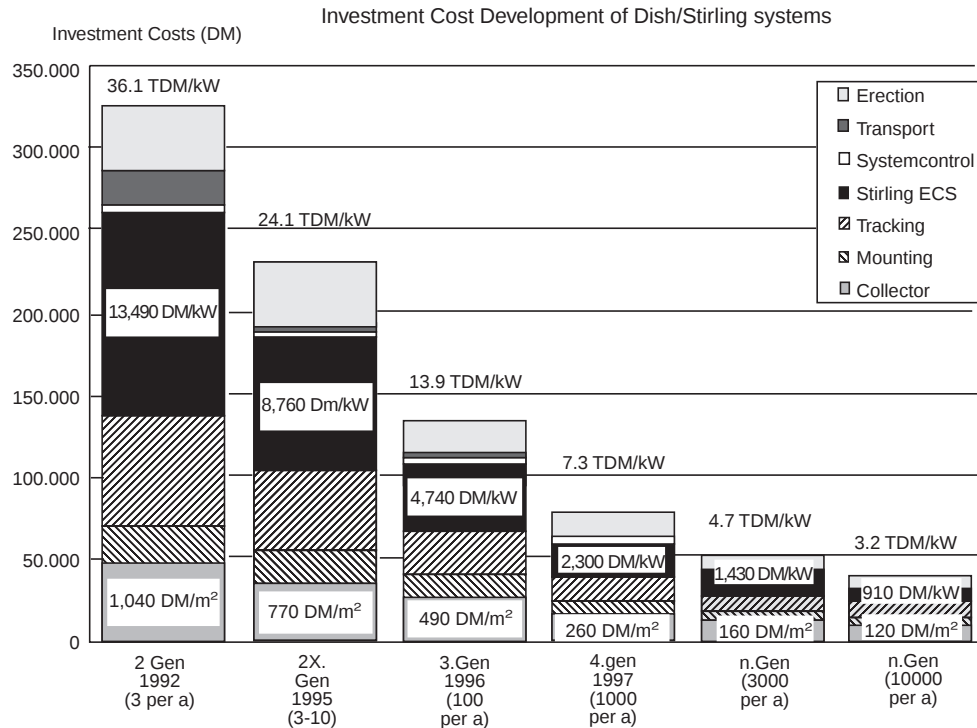


Fig. 11. Expected D/S-system cost with increasing number of units produced.

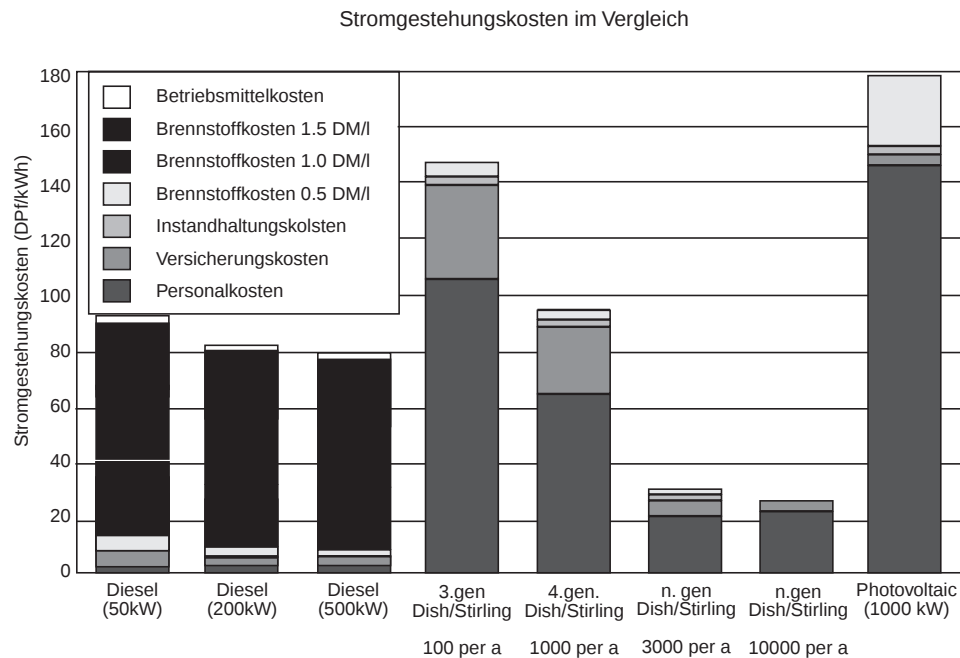


Fig. 12. Calculated levelized energy costs for D/S-system in comparison with fossil-fueled plants (Diesel).

with the distributed collector systems, there is conventional thermal power plant technology: The heat transfer medium is carried by pipes to a power plant at the base of the tower and there drives a turbine coupled to a generator.

Up to now six such plants have been built in the

United States, in Southern Europe and Japan, the largest being the 10 MW plant at Barstow, California, using steam as the heat transfer medium.

Further development is needed on system integration and cost reduction of the individual components. Obviously, cheap and accurate heliostats which make up 1/3

of total plant costs are of vital importance. At present most concentrators consist of several individual mirrors which are mounted together on structures able to track the sun around two axes (Fig. 13). Tracking is computer-controlled to guarantee precise focus. The stretched membrane technology as described above here again is the right answer with one continuous membrane as against the individual mirrors. In this case of a long focal length, the membrane remains in the elastic range and its focus is adjusted merely by varying the internal underpressure. Two prototype stretched membrane heliostats have been installed in Almeria, one with a diameter of 7.5 m using the pedestal of a standard heliostat (Fig. 14) and one with a diameter of 14 m with a much more precise and robust azimuthal tracking system, as described for D/S (Fig. 15). Especially the latter one has more than fulfilled all requirements and thus tension structures have provided a significant progress for CRS-solar power plants as well [6].

5. Solar chimneys

The solar chimney combines three well-known technologies — the greenhouse, the chimney, and the turbine — in a novel way (Fig. 16) [7]. Incident solar radi-

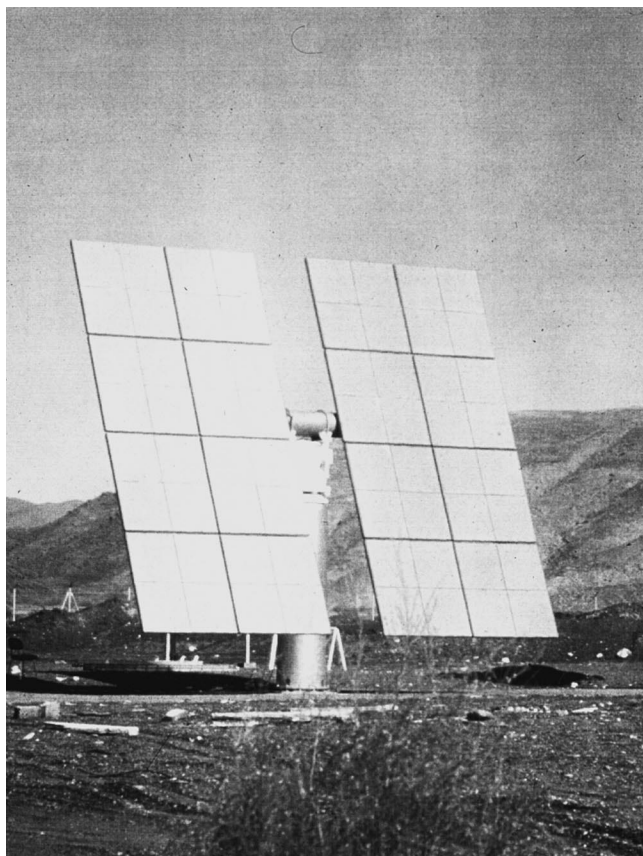


Fig. 13. A conventional faceted heliostat.

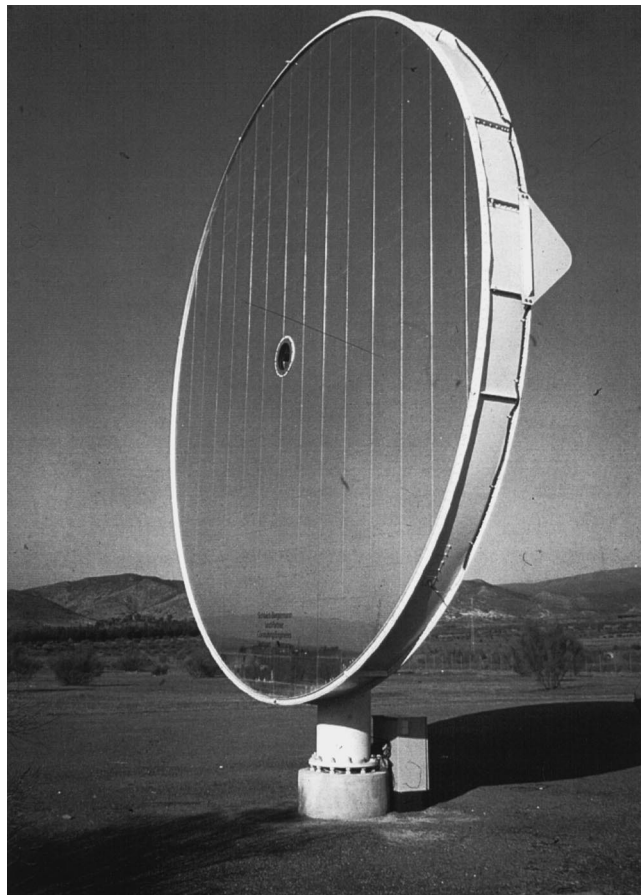


Fig. 14. A first stretched metal membrane heliostat.

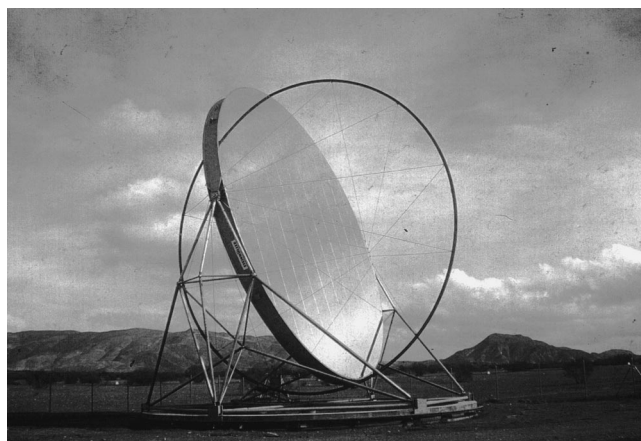


Fig. 15. An improved stretched metal membrane heliostat.

ation heats the air under a large transparent collector roof. The temperature difference causes a pressure drop over the height of the chimney resulting in an upwind which is converted into mechanical energy by turbines and then into electricity via conventional generators.

This solar energy system has many technological and physical advantages:

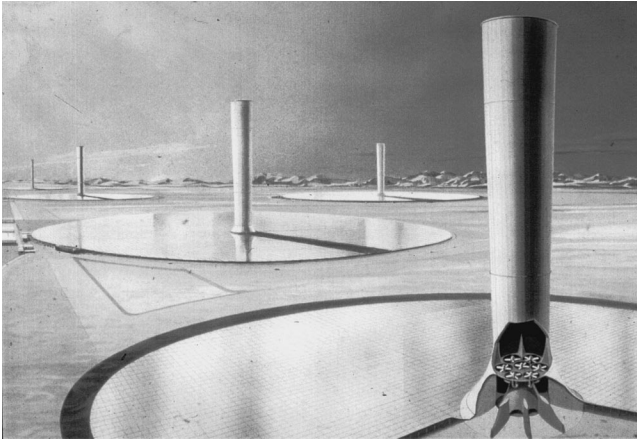


Fig. 16. Drawing of several large (100-200 MW) solar chimneys in a desert.

- Global radiation, including diffuse radiation when the sky is overcast, can be exploited.
- The natural storage medium — the ground — guarantees operation at a constant rate until well into the hours of darkness (and throughout the night with large-scale installations). If in addition black water-filled tubes are placed on the ground underneath the roof (Fig. 17), a continuous 24 hours electricity production can be achieved (Fig. 18).
- There are no moving parts, nor are there parts that require intensive maintenance aside from the turbine and the generator.
- Not even water is required to cool mechanical parts.
- Its simple, low-cost design and materials (glass, concrete, steel) make solar chimney systems applicable to less industrialised countries. Labour represents a high portion of the installation costs. This would stimulate the local labour market, while at the same time helping to keep overall costs down.

There is in fact no optimum physical size for solar chimneys. The same output may result from a large

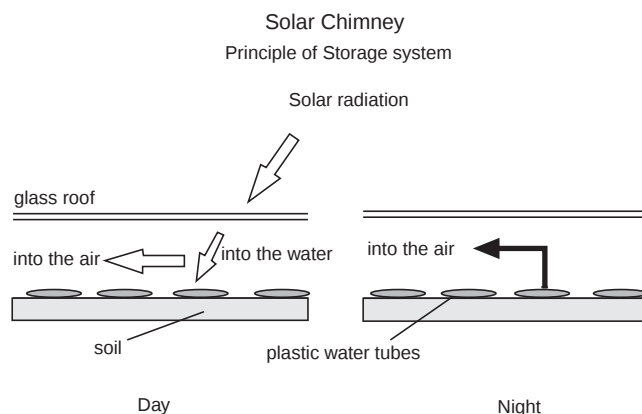


Fig. 17. Principle of heat storage underneath the roof using water-filled black tubes.

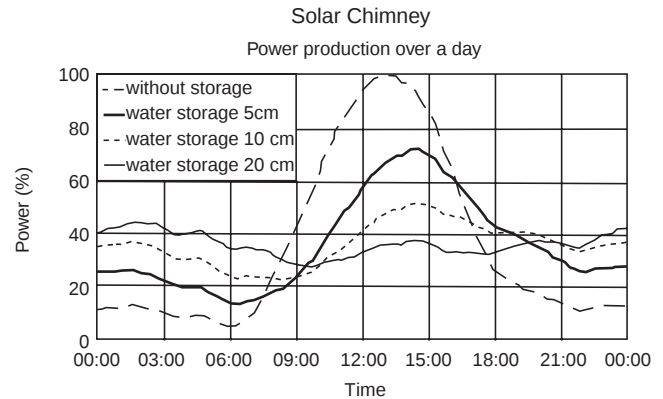


Fig. 18. Electricity output during 24 h as a function of the thickness of the water layer.

chimney with a small collector roof area and vice versa. Thus, to decide the optimum dimensions of chimney height against collector radius, the specific construction costs of these items must be known. If glass is cheap but concrete expensive, a large collector and low chimney is preferable, and vice versa. Broadly, to achieve a maximum output of (30) 200 MW at an irradiance of 1000 W/m^2 , the roof must have a diameter of (2200) 4000 m if the chimney has a height of (750) 1500 m. If black water-filled tubes are placed on the soil underneath the roof (Fig. 17) for a continuous 200 MW full load 24 hours electricity production the diameter of the roof must be increased to 7200 m. Now this solar chimney from a solar radiation of $2300 \text{ kWh/m}^2\text{a}$ extracts about 1500 GWh/a , in fact a power plant.

From a technological point of view, the solar chimney heavily depends on tension structures. The collector roof, responsible for almost 50% of the total cost must be as economical as possible. For that the glass panels are placed on suspended stress ribbons made from steel slats, spaced 1 m. They are supported by underslung girders resting on steel tubular columns $9/9 \text{ m}^2$. Tests on a prototype solar chimney in Manzanares/Spain has shown that this is a most efficient and durable structure (Figs. 19 and 20).

The turbines are basically more closely related to the pressure-induced water turbines than to the velocity-induced natural wind power plants. Therefore, the builders of hydroelectric power plants aided us in the development and calculation. Either several horizontal axis engines are placed around the chimney base or — the cheaper solution — one large, say 200 MW turbine with a vertical axis is placed in the chimney's diameter (Fig. 21).

For the chimney itself we thoroughly compared the possible construction methods and the materials such as covered steel framework with cable nets, membranes, trapezoidal metal sheet etc., just to discover that for all the desert countries in question the reinforced concrete

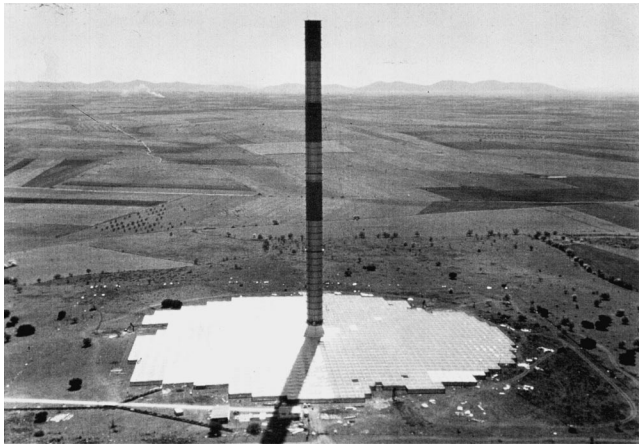


Fig. 19. The solar chimney in Manzanares/Spain.



Fig. 20. The glass collector roof of a solar chimney.

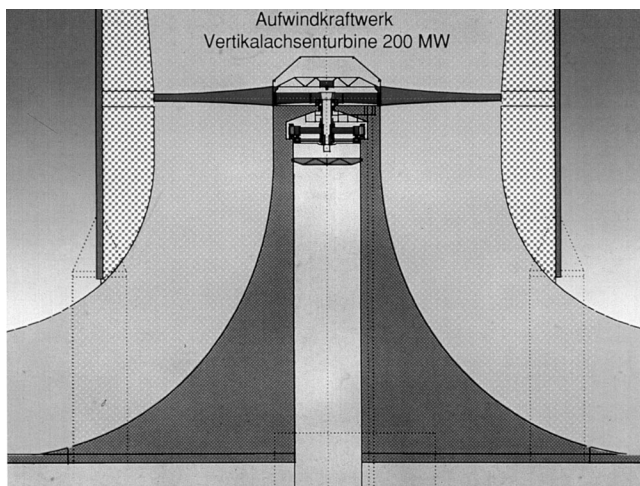


Fig. 21. 200 MW vertical axis in the shaft of the solar chimney.

tube promised the longest life-span at the most favourable costs. Technologically speaking they are nothing but cylindrical natural draught cooling towers with — as shown in Fig. 22 as an example — a diameter of

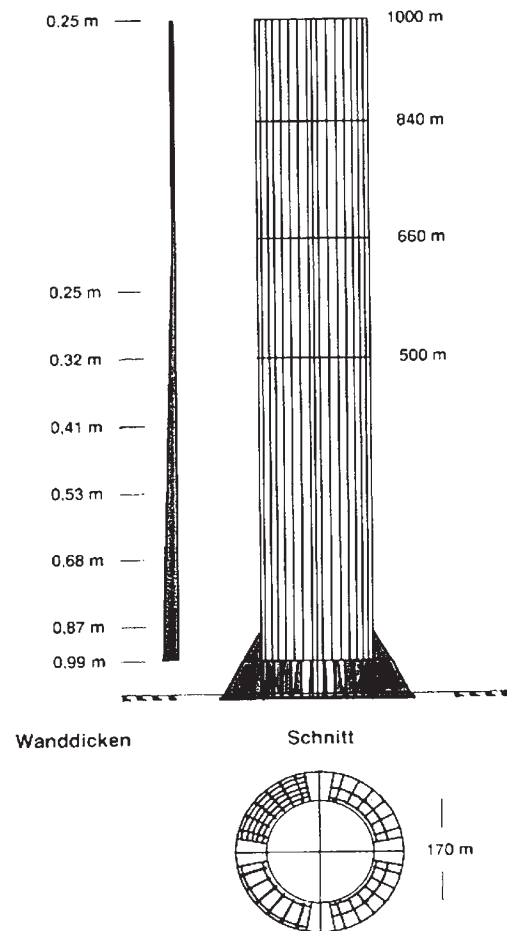


Fig. 22. Wall thickness of a chimney 1000 m high and 170 m in diameter.

170 m and height of 1000 m. The wall thickness decreases from 99 cm just above the support on radial walls to 25 cm halfway up, then remaining constant all the way to the top. Such thin-walled tubes will oval due to the wind suction especially at the flanks (Fig. 23).

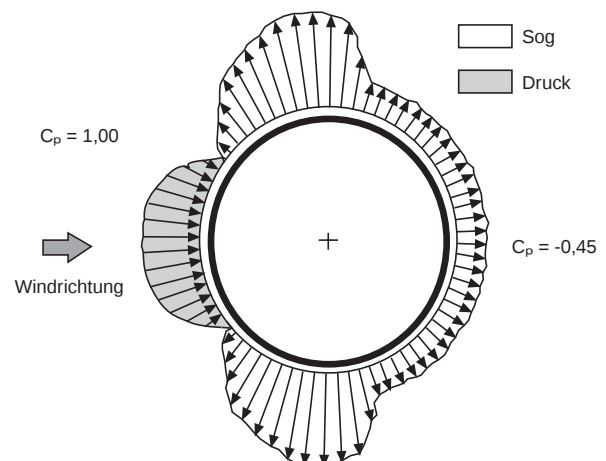


Fig. 23. Typical pressure distribution around the circumference of a cylindrical tube.

This tremendously increases the meridional compressive and tensile stresses if compared with the linear bending stresses of a cantilevering beam (Fig. 24, top left). The resulting loss in stiffness due to cracking of the reinforced concrete and the danger of buckling limit the height of natural draught cooling towers to about 200 m. But this ovalling can be efficiently counteracted by stiffening spoked wheels — tension structures — which have the same effect as diaphragms, hardly affecting the upwind. If the spokes are made of vertical steel slats stressed between a compression ring along the chimney's wall and a hub ring, such a spoked wheel is pre-stressed by its own weight, thus resulting in tension- and compression-resistant spokes (Fig. 25). It is seen from Fig. 24 that the meridional stresses in the chimney wall, shown in the diagrams across the diameter and the height, do undulate tremendously without any spoked wheels. But one spoked wheel at the top and another one or even three more further below do reduce the meridional stresses to an extent that tension disappears completely, succumb by the tube's dead load. Considering that the absolute volume under these stress diagrams is somehow proportional to the consumption of concrete and reinforcing steel, one arrives at in the obvious conclusion that tension structures, these spoked wheels, make such high towers for solar chimneys feasible.

Thus, with the support of construction companies, turbine manufacturers and the glass industry a rather exact cost estimate for a 200 MW solar chimney could be

compiled. Two big German utility companies determined the electricity producing costs compared to coal- and combined cycle power plants based on equal and usual methods (Fig. 26).

This clearly shows that calculated purely under business managerial aspects with a gross interest rate of 11% and a construction period of 4 years during which the investment costs increase already by 30% (!) electricity from solar chimneys is just 20% more expensive than that from coal.

In case of the solar chimney the interest on the investment governs the price of electricity, whereas in the case of fossil fuel power plants mainly the fuel costs are the deciding factor.

Merely reducing the interest rate to 8% would make electricity from solar chimneys competitive today (Fig. 27). The present still higher costs of solar electricity are balanced by several advantages:

- No ecological damage and no consumption of resources, not even for the construction, because a solar chimney predominantly consists of glass and cement which is sand plus self-made energy.
- The (high) investment costs are almost exclusively due to labour costs. This creates jobs, and
- a high net product for the country with increased tax income and reduced social costs (= human dignity, social harmony), and in addition
- no costly imports of coal, oil, gas which is especially

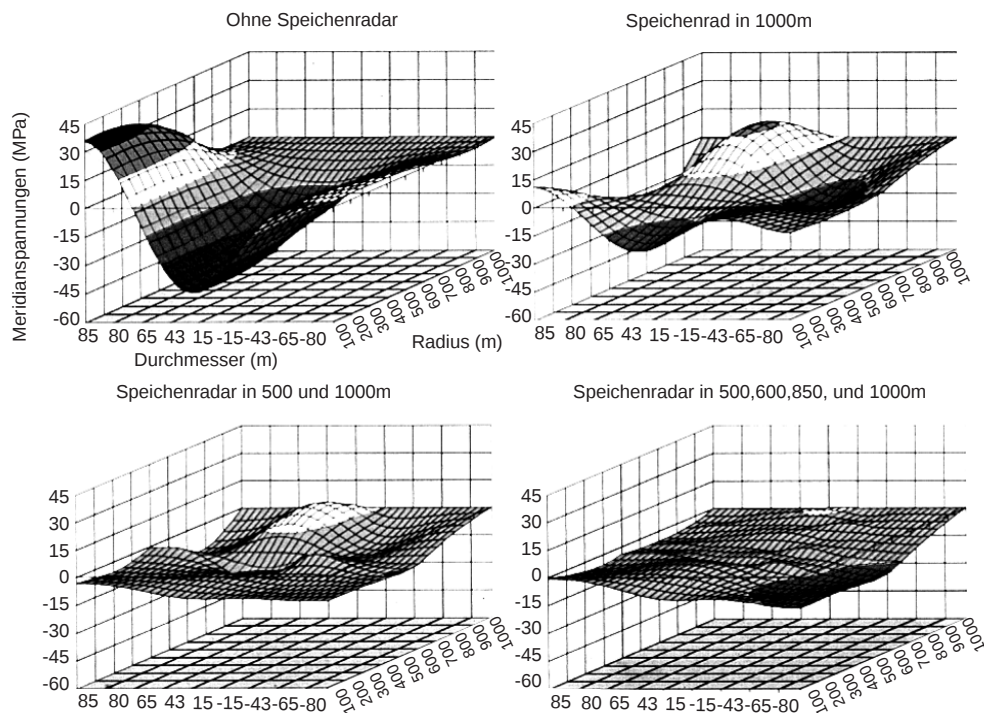


Fig. 24. Meridional stresses in the chimney according to Fig. 22, around its periphery and along its height depending on the number of stiffening spoked wheels (Speichenräder).

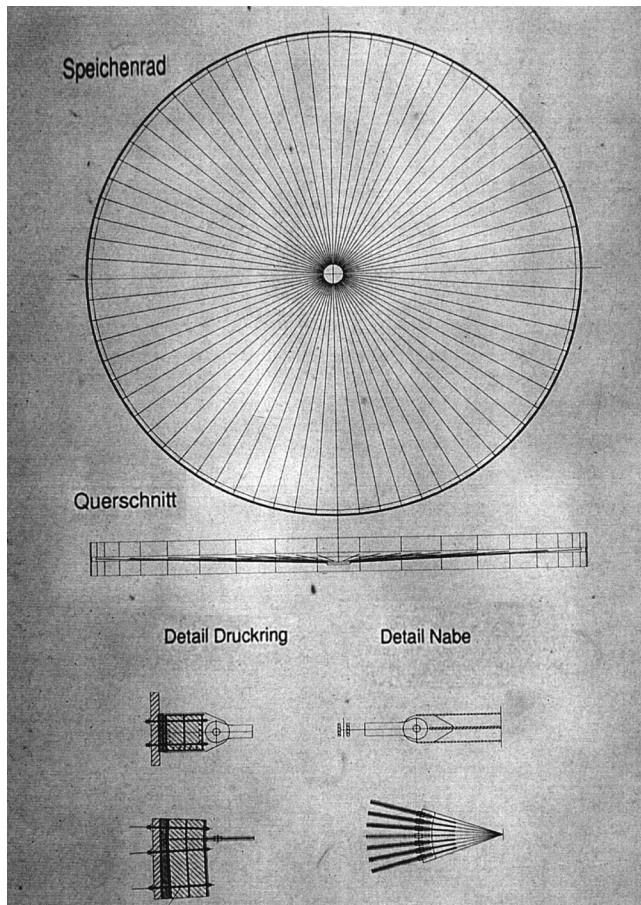


Fig. 25. Spoked wheels, the spokes are made of vertical steel slats.

Stromgestehungskosten im Vergleich

Anteil der	Aufwind Pf/kWh	Kohle Pf/kWh	2 x GuD Pf/kWh
Investition	11.32	3.89	2.12
Brennstoff	0.00	3.87	6.57
Personal	0.10	0.78	0.31
Instandhaltung	0.52	0.92	0.83
Versicherung	0.01	0.27	0.12
Sonstige Betriebskosten	0.00	1.16	0.03
Steuern	2.10	0.69	0.37
Gesamt	14.05	11.58	10.35
Inbetriebnahme im Jahr 2001 Leistung: 400 MW Betriebsstunden: 7445 h/a Jahresenergie: 2878 GWh			
Eigenkapital 1/3 zu 13.5% Fremdkapital 2/3 zu 8% Gesamtzinssatz: 10.67% Steuersatz: 30%			

Fig. 26. Electricity producing costs (Stromgestehungskosten) from solar chimney, coal and combined cycle power plants according to the present business managerial calculation (overall interest rate: 10.7%).

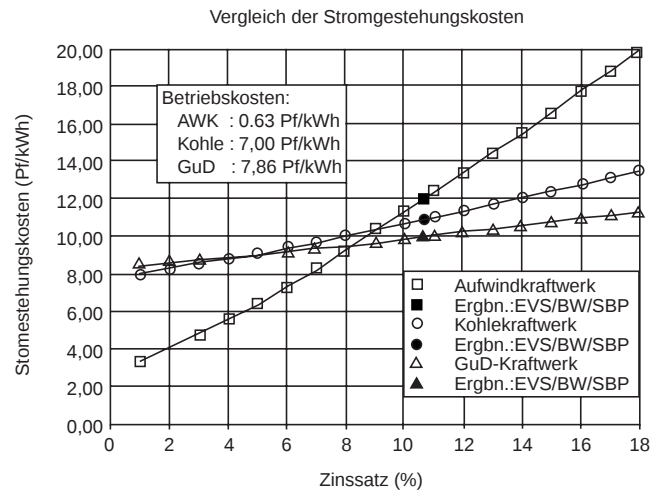


Fig. 27. Electricity producing costs (Stromgestehungskosten) from solar chimney (Aufwindkraftwerk), coal (Kohle) and combined cycle power plants (GuD-Kraftwerken) depending on the interest rate (Zinssatz).

beneficial for the developing countries releasing means for their development.

We have no choice but to do something for the energy consent, the environment and above all for the billions of underprivileged people in the Third World. But we should not offer them hand-outs, a multiple of which we deceitfully regain by imposing a high interest rate on their debt. Instead we should opt for global job sharing. If we buy solar energy from Third World countries, they can afford our products. A global energy market with an essential solar contribution beyond hydropower is no utopian dream. If we really want to we can do it!

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